# PHYSICAL, CHEMICAL, AND THERMAL CHARACTERIZATION OF WHEAT FLOUR MILLING COPRODUCTS[1,2]


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## ABSTRACT


*Hard red winter (HRW) and hard red spring (HRS) wheat milling coproducts (bran, germ, shorts, and red dog) from three commercial flour mills and the Kansas State University pilot mill were evaluated for differences in physical, chemical, and thermal properties. The ranges of bulk density for bran, germ, and red dog determined at three moisture levels were 146.5 to 205.2 kgm$^{-3}$, 269.2 to 400.6 kgm$^{-3}$, and 298.9 to 398.1 kgm$^{-3}$, respectively. The true density ranking order was: red dog > shorts = germ > bran, independently of the moisture level. Red dog had the smallest geometrical mean diameter with the highest variation (coefficient of variation of 23.8%). There was a significant ($P < 0.05$) difference among wheat blends and milling flows in the thickness of bran and germ at the same particle separation size. The image analysis study determined that the equivalent projected area diameter of bran at the same*


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*separation size was significantly (P<0.05) larger than that of germ. The ratio between the equivalent projected area diameter and the particle thickness were within ranges of 15.7 to 37.6 for bran and 15.5 to 32.2 for germ particles. The chemical composition (ash, protein, lipids and fiber) ranges were determined for each coproduct. Ranges of thermal conductivity for bran, germ, shorts, and red dog were 0.049 to 0.074, 0.054 to 0.0907, 0.057 to 0.076, and 0.063 to 0.080 $W(mK)^{-1}$, respectively. Specific heat of coproducts, measured with a differential scanning calorimeter, exhibited a wider range [1.08 - 1.94 $kJ(kgK)^{-1}$] than that observed in whole wheat kernels and wheat flour. The variability observed among the samples was due to the different wheat sources and characteristic milling flows for the flour mills.*

## INTRODUCTION

In the U.S. dry wheat milling converts about 70 to 75% of the wheat into flour, with the remainder as coproducts which are typically called bran, germ, shorts, and red dog. Coproducts, also referred to as millfeeds, are second only to soybean meal as the most common feed ingredients in the commercial feed industry (Blasi *et al.* 1998) and are widely used as ingredients in ready-to-eat breakfast cereals and health-food products.

Each wheat flour mill has characteristic mill flows that produce unique flours and coproducts. Coproducts can be described both botanically and commercially. Bran, the outermost layers of the wheat comprised of the pericarp, seedcoats, nucellus, and aleurone layer, consists of the large pieces (usually over 0.900 mm). Shorts consist of finer particles of wheat bran, portions of wheat germ, unseparated wheat flour, and the offal of the "tail of the mill" and by definition must contain no more than 7% crude fiber. Germ contains the embryo and scutellum and is almost completely free of other wheat kernel constituents. Red dog consists of the offal from the "tail of the mill" together with some fine particles of wheat bran, wheat germ, and wheat flour and must contain no more than 4% crude fiber (Wingfield 1989).

Characterization of coproducts is the first step in food product formulation and development. Basic understanding of the properties of those coproducts can lead to improvement of both the product quality and ease of product development. Although much research has been conducted on the characterization of whole grains, there has been little current research on the characterization of coproducts produced from wheat flour milling.

Fundamental knowledge of physical characteristics and their variability, such as true density, bulk density, moisture and particle size distribution, are helpful to ensure proper handling, storage, and drying, as well as help to determine the overall design of the processing system. Several studies have been conducted on the relationship between true density and moisture content of grains or their products (Browne 1962; Chung and Converse 1971; Hall and Hill 1974; Wang *et al.* 1995). Appel (1985) and Farrell *et al.* (1967) also determined the bulk density of some coproducts, but did not relate this property to moisture content. Wheat is conditioned to moisture levels higher than the storage and shipping moisture content, the response of the physical characteristics of the wheat coproducts to moisture variations is very important. Also, because new wheat varieties are constantly introduced in the market to achieve specific gains in wheat production yields and to properly compete in world markets, the study of the wheat coproducts from commercial blends needs to be conducted.

Accurate description of particle size in a raw material is essential to feed formulation and manufacturing because it affects the feed's processing conditions and nutritional efficiency. The importance of particle size in feed manufacturing was reported by several researchers (Goodband and Hines 1987; Goodband *et al.* 1995; Healy *et al.* 1994; Ohh *et al.* 1983; Wondra *et al.* 1992). The most common method for determining particle size distribution of ground materials is the standard sieving method of the American Society of Agricultural Engineers Method S319.2 (ASAE 1996). This method also estimates surface area of material by assuming the shape of particles as spherical. Bran and germ, however, are not spherical and as a result the current sieving method for determining particle size is not adequate for measuring particle size in animal feed. New techniques using image analysis to measure the particle size of bran and germ from wheat flour milling are available and could be adapted to the feed and livestock industries to provide a more uniform and consistent determination of particle size of ingredients (Kim and Flores 1999).

The chemical composition of the raw material is another important aspect in feed formulation. Accurate measurement of chemical constituents is necessary for successful development of new products and for balancing nutrients within products. Several studies have measured the chemical composition of coproducts (Farrell *et al.* 1967; Grewe and LeClerc 1943; Ranhotra *et al.* 1971; Waggle *et al.* 1967). General chemical composition of feed ingredients is listed in the annual publications of Feed Industry Red Book (Hubble 1998) and Feedstuffs Reference Issue (Dale 1998), however, these sources do not provide information about recent values for commercial blends.

Coproducts are subjected to various types of thermal processes such as cooking, cooling, drying, extrusion, and freezing before consumption. Thermal measurements including thermal conductivity and diffusivity are fundamental in the proper design of thermal processes. There are no thermal properties for milling coproducts reported in the literature. Thermal conductivity measurements of food materials are based on the quasi-steady state techniques and transient techniques. The quasi-steady state techniques, developed by Fitch (1935), are used to measure an individual sample of food. Even though those methods can be used to measure the thermal conductivity of bulk material, they require sample thickness for the calculation of thermal conductivity (a property not always known for bulk materials). The most common method for measuring thermal conductivity of bulk materials, specifically grains and coproducts, is a line source (Van Der Held and Van Drunen 1949). An advantage of this method is that sample geometry is not important for the accurate measurement of thermal conductivity. With a known amount of heat generated from a heat source and temperature rise over time, the thermal conductivity can be determined with Eq. (1):

$$k = \frac{Q}{4\pi(T_2 - T_1)} \ln\left(\frac{t_2}{t_1}\right) \tag{1}$$

where $k$ is the thermal conductivity [W(mK)$^{-1}$], Q is the heat (W), $T_1$ is the temperature at $t_1$ (°C), $T_2$ is the temperature at $t_2$ (°C), and $t_1$ and $t_2$ are time 1 and 2 (s), respectively.

The most common methods for determining specific heat are a mixture of direct and indirect methods and differential scanning calorimetry (DSC). Kazarian and Hall (1965) used the direct method of mixture to determine the specific heat of wheat flours and grains. However, with the direct method, mixing a solid material with a liquid, the heat exchange medium can generate serious errors for hygroscopic materials due to changes of chemical entities (Rahman 1995). The indirect method, using an encapsulated sample in a copper cylinder immersed into a heat exchange medium, can eliminate errors in the direct method. However, building an apparatus that produces accurate results is extremely delicate work and requires tedious sample preparation (Hwang and Hayakawa 1979). The dynamic features of DSC allow the determination of specific heat as a function of moisture content and temperature (Tang *et al.* 1991).

The objective of this study was to characterize the physical, chemical, and thermal properties of coproducts produced from different wheat flour mills. The characterization consisted on the determination of: (1) true and bulk densities of coproducts and the effect of moisture content on these physical properties; (2) particle size and its distribution using the sieving method and image analysis; (3) chemical composition of coproducts; and (4) thermal conductivity and the effect of moisture content on the thermal conductivity. Also, because of constant changes in milling flows in commercial flour mills and the introduction of new wheat varieties, results of this study were compared among coproducts and previously reported results, when the information was available.

## MATERIALS AND METHODS

### Sample Collection and Preparation

A total of 32 representative samples of the wheat coproducts manufactured in wheat flour mills were obtained from four flour mills in the U.S. Midwest. The coproduct samples were manufactured in three commercial flour mills (sources kept undisclosed for privacy purposes) and the Kansas State University (KSU) pilot mill (Table 1). The coproducts raw material were hard red winter (HRW) and hard red spring (HRS) wheat commercial blends, the two major blends used by the U.S. milling industry. Samples from the KSU pilot mill (samples A-1 and A-2) and a commercial flour mill (samples B-1 and B-2) were from two different HRW wheat blends. The second commercial flour mill provided two sets each of bran, germ, and red dog from HRW wheat blends (samples C-1 and C-2) and from HRS wheat blends (samples C-3 and C-4). No shorts samples were provided by the second commercial flour mill because the mill does not produce them as a finished product. The third commercial flour mill provided a set of HRS wheat coproduct samples (D-1). Therefore, coproduct samples A-1 through C-2 are from blends of HRW wheat, while C-3, C-4, and D-1 are coproducts of HRS wheat blends.

TABLE 1.
COPRODUCT SAMPLES FROM COMMERCIAL AND PILOT MILLS

| Mill Source | Wheat class blend | Co-products | | | |
|---|---|---|---|---|---|
| | | Bran | Germ | Shorts | Red dog |
| KSU pilot mill (A-1 and A-2)[a] | HRW | 2 | 2 | 2 | 2 |
| Commercial mill 1 (B-1 and B-2)[a] | HRW | 2 | 2 | 2 | 2 |
| Commercial mill 2 (C-1, C-2, C-3, and C-4)[a] | HRW<br>HRS | 2<br>2 | 2<br>2 | np[b]<br>np[b] | 2<br>2 |
| Commercial mill 3 (D-1)[a] | HRS | 1 | 1 | 1 | 1 |
| Total | | 9 | 9 | 5 | 9 |

[a] Sample code.
[b] Shorts were not produced in commercial mill 2.

Moisture content of coproducts was determined with Method 44-15A of the Association of American Cereal Chemists (AACC 2000). Samples were conditioned at three different moisture levels: 8, 12, and 16% (wet basis) by adding water and keeping for 48 h in sealed plastic bags at room temperature (24 ± 2C). Drying of samples was done in an air oven at 50C. The final moisture content of the tempered or dried samples was checked and the processes were repeated until the desired moisture content was achieved.

## Physical Properties

Bulk density was measured using a Winchester Bushel Weight Tester (Burrows Equipment Co., Evanston, IL) following the test weight U.S. Grain Standards (USDA 1997) approved procedure and converted into $kgm^{-3}$. True density was measured with a multipycnometer (Quantachrome Corp., MVP-1, Boynton Beach, FL) following the procedure of Chang (1988). Particle size distribution of the coproducts was determined using the ASAE sieving method S319.2 (1996) with a Ro-Tap sieve shaker (W.S. Tyler, Inc., Mentor, OH) and a complete set of U.S. standard sieves. Fifty bran and germ individual particles were randomly collected from each fraction retained on each of the U.S. Standard sieves #30 and lower (sieve opening greater than 0.594 mm) and measured for thickness and projected area diameters. The thickness of the particles was manually measured with a micrometer (Didimatic, Mitutoyo, Japan) and the projected area diameters of the particles was determined with an image processing unit (CCD XC-77 Sony Video Camera, Tokyo, and Quantim version 2.3, Zedec Technologies, Burlington, NC). Equivalent projected area diameter was then calculated using Eq. (2) (Allen 1981):

$$d_a = \sqrt{\frac{4A}{\pi}} \qquad (2)$$

where $d_a$ is the equivalent projected area diameter (mm) and A is the projected area ($mm^2$). The bran and germ particles retained on the sieves with openings of 0.420 mm or less, approximately 2% of total weight, were not included in the image analysis.

## Chemical Composition

Moisture, protein, ash, fiber, and crude fat contents were determined by the AACC methods 44-15A, 46-16, 08-03, 32-06, and 30-25 (AACC 2000), respectively.

## Thermal Properties

Thermal conductivity of coproduct samples was determined with a line heat-source probe constructed following the procedures of Baghr-Khandan *et al.* (1981) and calibrated using glycerin as standard material. To maintain constant heat generation by the heat source a power supply unit was used (BK model 1760, Maxtec International, Chicago). Temperature rise over time was recorded with a data acquisition system (Fluke Hydra model 2656A, John Fluke Co., Everett, WA). The sample cup was submerged in a water bath (PolyScience, Niles, IL) at 25 ± 1C during the entire experiment. The measurements were repeated four times. Thermal conductivity was calculated using Eq. (1).

### Specific Heat

Specific heat was determined on 16 randomly selected streams, four per coproduct, with a differential scanning calorimeter (DSC, Pyris 1, Perkin Elmer, Wellesley, MA) following the E1269-94 method of the American Society of Testing and Materials (ASTM 1994) with a synthetic sapphire for calibrating DSC at 26.9C.

### Experimental Design and Statistical Analysis

The coproducts true and bulk densities were examined using one-way analysis of variance (ANOVA) with a completely randomized experimental design. The effect of particle separation size and wheat class on thickness and equivalent projected area diameter of bran and germ particles was studied using Fisher's least significant difference (LSD) test at $\alpha = 0.05$. The Statistical Analysis System (SAS, version 7.00, SAS Institute, Cary, NC) was used for ANOVA and LSD tests. The average, standard deviation (STD), coefficient of variation (CV), and a simple linear regression were calculated with Quattro Pro (version 7, Ottawa, Ontario, Canada). The thickness and projected area were measured once and thermal conductivity was measured five times. All other measurements were repeated twice.

## RESULTS AND DISCUSSION

### Physical Properties

Results of true and bulk density measurements associated with the change in moisture content for coproducts are presented in Table 2. True density of bran for HRS wheat blends (1260.0 to 1291.5 $kgm^{-3}$ at 8% moisture content) was higher than that of HRW wheat blends (1127.1 to 1186.0 $kgm^{-3}$ at 8% moisture content) at all moisture levels. Samples from the same flour mill (samples C-1, 2, 3, and 4) showed higher true density (1094.5 - 1291.5 $kgm^{-3}$ at all three moisture contents) for HRS wheat blends (samples C-3 and 4) than that (1067.6-1177.1 kgm$^{-3}$ at all three moisture contents) of HRW wheat blends (samples C-1 and 2).

TABLE 2.
TRUE AND BULK DENSITY OF THE COPRODUCTS AT DIFFERENT MOISTURE CONTENT (kgm$^{-3}$)

| Sample | MC[a] | Bran True | Bran Bulk | Germ True | Germ Bulk | Shorts True | Shorts Bulk | Red dog True | Red dog Bulk |
|---|---|---|---|---|---|---|---|---|---|
| A-1[b] | 8 | 1186.0 | 171.3 | 1245.6 | 323.6 | 1240.0 | 274.6 | 1309.5 | 379.8 |
| | 12 | 1102.0 | 163.9 | 1232.1 | 303.6 | 1224.4 | 264.9 | 1295.2 | 354.2 |
| | 16 | 1001.9 | 153.9 | 1209.0 | 273.1 | 1215.8 | 260.7 | 1266.3 | 345.2 |
| A-2[b] | 8 | 1148.2 | 173.7 | 1243.0 | 322.6 | 1244.7 | 305.1 | 1297.6 | 351.8 |
| | 12 | 1080.1 | 170.8 | 1230.1 | 309.2 | 1226.2 | 299.5 | 1281.7 | 332.2 |
| | 16 | 1022.8 | 165.1 | 1216.3 | 288.9 | 1218.9 | 290.2 | 1266.6 | 306.7 |
| B-1[b] | 8 | 1127.1 | 155.2 | 1249.4 | 358.7 | 1247.0 | 272.4 | 1311.6 | 398.1 |
| | 12 | 1059.8 | 152.7 | 1202.1 | 342.9 | 1234.4 | 263.4 | 1298.7 | 384.7 |
| | 16 | 975.4 | 146.5 | 1111.9 | 313.9 | 1221.5 | 262.7 | 1290.2 | 359.7 |
| B-2[b] | 8 | 1157.7 | 155.6 | 1233.9 | 400.6 | 1261.1 | 298.7 | 1309.0 | 378.4 |
| | 12 | 1071.2 | 154.1 | 1211.0 | 370.5 | 1235.0 | 288.6 | 1294.7 | 371.5 |
| | 16 | 999.9 | 146.5 | 1192.0 | 358.0 | 1218.6 | 287.8 | 1277.9 | 347.3 |
| C-1[b] | 8 | 1174.1 | 197.3 | 1258.9 | 326.8 | n/p[d] | n/p[d] | 1300.2 | 338.6 |
| | 12 | 1108.4 | 191.9 | 1241.0 | 321.5 | n/p[d] | n/p[d] | 1285.0 | 325.2 |
| | 16 | 1079.5 | 186.3 | 1226.5 | 304.5 | n/p[d] | n/p[d] | 1268.3 | 317.4 |
| C-2[b] | 8 | 1141.2 | 205.2 | 1259.4 | 306.7 | n/p[d] | n/p[d] | 1294.6 | 322.8 |
| | 12 | 1096.6 | 180.8 | 1253.5 | 303.5 | n/p[d] | n/p[d] | 1283.7 | 306.2 |
| | 16 | 1067.6 | 175.4 | 1234.3 | 280.7 | n/p[d] | n/p[d] | 1267.5 | 298.9 |
| C-3[c] | 8 | 1264.8 | 199.4 | 1248.3 | 327.5 | n/p[d] | n/p[d] | 1308.3 | 360.7 |
| | 12 | 1209.2 | 186.7 | 1242.6 | 300.2 | n/p[d] | n/p[d] | 1290.6 | 343.2 |
| | 16 | 1107.2 | 183.3 | 1230.7 | 269.2 | n/p[d] | n/p[d] | 1276.1 | 338.5 |
| C-4[c] | 8 | 1291.5 | 190.3 | 1255.2 | 313.4 | n/p[d] | n/p[d] | 1305.2 | 346.6 |
| | 12 | 1209.3 | 183.4 | 1245.7 | 308.3 | n/p[d] | n/p[d] | 1283.8 | 326.0 |
| | 16 | 1094.5 | 174.2 | 1233.8 | 289.6 | n/p[d] | n/p[d] | 1274.7 | 323.9 |
| D-1[c] | 8 | 1260.0 | 179.9 | 1263.0 | 332.9 | 1237.3 | 284.5 | 1286.9 | 372.1 |
| | 12 | 1189.4 | 178.3 | 1250.0 | 287.1 | 1226.1 | 274.3 | 1276.4 | 360.6 |
| | 16 | 987.4 | 168.9 | 1228.1 | 269.3 | 1220.4 | 269.6 | 1263.1 | 350.7 |

[a] Moisture content in percentage wet basis.
[b] Samples A-1 through C-2 are coproducts from HRW wheat blends.
[c] Samples C-3, C-4, and D-1 are coproducts of HRS wheat blends.
[d] Shorts were not produced in commercial mill 2.

The ranges of bulk density for bran, germ, and red dog determined at three moisture levels were 146.5 to 205.2 $kgm^{-3}$, 269.2 to 400.6 $kgm^{-3}$, and 298.9 to 398.1 $kgm^{-3}$, respectively. Appel (1985) reported bulk density ranges for bran (176 to 256 $kgm^{-3}$), germ meal (448 to 513 $kgm^{-3}$), and red dog (352 to 448 $kgm^{-3}$) that were higher than those determined in this study. As a result of particle expansion and changes in surface characteristics for all four coproducts, true and bulk density decreased as the moisture increased. There was a significant difference ($P<0.05$) in true and bulk density among the four coproducts. The true density ranking order was: red dog > shorts = germ > bran, independently of the moisture level. The coefficient of determination ($R^2$) for moisture content as independent variable in determining density ranged from 0.913 to 0.999 and from 0.817 to 0.999 for true density and bulk density, respectively, for all four coproducts. Similar results were reported by several researchers for whole grains and grain products (Browne 1962; Chung and Converse 1971; Hall and Hill 1974; Wang *et al.* 1995).

The geometric mean diameter and the geometric standard deviation of the coproducts obtained using the ASAE sieving method S319.2 are shown in Table 3. The overall geometric mean diameter average (1.222 mm) and geometric standard deviation (1.630) for bran were slightly higher than those for germ (1.195 and 1.413 mm, respectively). This particle size difference is a

TABLE 3.
GEOMETRIC MEAN DIAMETER AND GEOMETRIC STANDARD DEVIATION OF PARTICLE SIZE USING THE SIEVE METHOD (mm)

| Sample | Bran | | Germ | | Shorts | | Red dog | |
|---|---|---|---|---|---|---|---|---|
| | $d_{gw}$[a] | $S_{gw}$[b] | $d_{gw}$[a] | $S_{gw}$[b] | $d_{gw}$[a] | $S_{gw}$[b] | $d_{gw}$[a] | $S_{gw}$[b] |
| A-1[c] | 1.245 | 1.464 | 1.274 | 1.361 | 0.533 | 1.795 | 0.199 | 1.391 |
| A-2[c] | 1.314 | 1.612 | 1.226 | 1.434 | 0.552 | 1.576 | 0.183 | 1.323 |
| B-1[c] | 1.162 | 1.546 | 1.237 | 1.335 | 0.534 | 1.416 | 0.152 | 1.242 |
| B-2[c] | 1.236 | 1.546 | 1.156 | 1.295 | 0.618 | 1.558 | 0.138 | 1.265 |
| C-1[c] | 1.425 | 1.656 | 1.051 | 1.397 | n/p[e] | n/p[e] | 0.220 | 1.419 |
| C-2[c] | 1.282 | 1.720 | 1.149 | 1.413 | n/p[e] | n/p[e] | 0.220 | 1.406 |
| C-3[d] | 0.950 | 1.719 | 1.187 | 1.498 | n/p[e] | n/p[e] | 0.214 | 1.398 |
| C-4[d] | 1.031 | 1.857 | 1.133 | 1.424 | n/p[e] | n/p[e] | 0.220 | 1.406 |
| D-1[d] | 1.351 | 1.546 | 1.341 | 1.557 | 0.543 | 1.748 | 0.308 | 1.635 |

[a] Geometric mean diameter.
[b] Geometric standard deviation.
[c] Samples A-1 through C-2 are coproducts from HRW wheat blends.
[d] Samples C-3, C-4, and D-1 are coproducts of HRS wheat blends.
[e] Shorts were not produced in commercial mill 2.

consequence not only of the morphological characteristics of the pericarp and germ but of the milling operations. The milling operations for germ are less severe than those for bran, even though germ goes through a greater number of grinding steps than bran. Separation of germ from bran and endosperm is more sophisticated, it involves separating by particle size and density using sifters and purifiers, respectively; while bran is separated mostly by particle size using sifters. The overall average geometric mean diameter for shorts and red dog were 0.556 and 0.206 mm and the geometric standard deviations were 1.619 and 1.387, respectively. The particle size characteristics of red dog were more dependent on the milling flow of each specific mill than any other coproduct because it goes through more milling and separating steps than the other coproducts. Even though commercial mill 2 did not produce shorts, shorts might be included in the red dog final flow. The highest coefficient of variation (23.8%) was for red dog showing the largest diversity of particle size compared to the other coproducts.

Bran and germ particle thickness are shown in Table 4. The average thickness of bran particles ranged from 0.07 to 0.16 mm. Previous studies reported a narrower range (0.050 to 0.078 mm) of bran thickness determined by sectioning the kernels and examining under the microscope (Shellenberger and Morgenson 1949; Larken *et al.* 1951; Lineback *et al.* 1978). The thickness differences from this study and previous ones are because the bran samples in this study were obtained from commercial milling processes. Even though milling flows in this study contained a sufficient number of rolls and bran duster to separate endosperm from bran, the endosperm could not be completely separated from bran resulting in thicker bran particles. Also, thickness measured with a micrometer represents the maximum thickness. The average thickness of bran particles was significantly ($P<0.05$) larger (0.08 to 0.16 mm) than those of germ (0.08 to 0.13 mm) for same size, except for the particles collected on the U.S. Standard sieve #30 (F values ranges from 5.12 to 12.9 at $F_{crit} = 3.85$). A large variation was observed for the thickness of bran and germ particles as the coefficient of variation ranged from 11.2 to 40.8%. ANOVA and LSD showed that the average thickness of bran and germ particles was significantly different ($P<0.05$) for different particle size as LSD ranged from 0.008 to 0.015. The analyses also indicated a significant ($P<0.05$) difference among wheat blends and milling flows in terms of the thickness of both bran and germ at the same separation size (LSD ranged from 0.010 to 0.012).

Table 5 shows the average and one standard deviation for equivalent projected area diameter from the image analysis for bran and germ particles. The equivalent projected area diameter of bran at the same separation size was significantly ($P<0.05$) larger than that of germ (range of $F = 76.3$ to 812.3 at $F_{crit} = 3.85$). The coefficient of variation range for bran particles was from 7.3

to 13.5% while that for germ was from 5.3 to 16.4%. The different wheat classes and milling flows significantly ($P<0.05$) affected the equivalent projected area diameter for the particles separated using the same size sieves (LSD ranged from 0.690 to 0.146).

TABLE 4.
THICKNESS OF BRAN AND GERM FROM IMAGE ANALYSIS FOR DIFFERENT PARTICLE SEPARATION SIZE (mm)[a]

| Co-product | Sample | US Sieve # | | | | |
|---|---|---|---|---|---|---|
| | | 8 | 12 | 16 | 20 | 30 |
| Bran | A-1[b] | 0.15 ± 0.02 | 0.14 ± 0.02 | 0.13 ± 0.02 | 0.12 ± 0.03 | 0.10 ± 0.02 |
| | A-2[b] | 0.13 ± 0.03 | 0.12 ± 0.02 | 0.11 ± 0.02 | 0.09 ± 0.02 | 0.10 ± 0.02 |
| | B-1[b] | 0.12 ± 0.01 | 0.11 ± 0.02 | 0.09 ± 0.02 | 0.08 ± 0.03 | 0.08 ± 0.03 |
| | B-2[b] | 0.11 ± 0.01 | 0.10 ± 0.02 | 0.09 ± 0.01 | 0.08 ± 0.02 | 0.07 ± 0.03 |
| | C-1[b] | 0.16 ± 0.03 | 0.13 ± 0.03 | 0.12 ± 0.03 | 0.09 ± 0.03 | 0.08 ± 0.03 |
| | C-2[b] | 0.16 ± 0.04 | 0.14 ± 0.04 | 0.13 ± 0.04 | 0.11 ± 0.05 | 0.11 ± 0.03 |
| | C-3[c] | 0.14 ± 0.03 | 0.12 ± 0.02 | 0.11 ± 0.03 | 0.09 ± 0.03 | 0.08 ± 0.02 |
| | C-4[c] | 0.16 ± 0.03 | 0.12 ± 0.03 | 0.11 ± 0.03 | 0.09 ± 0.02 | 0.09 ± 0.03 |
| | D-1[c] | 0.14 ± 0.02 | 0.13 ± 0.03 | 0.12 ± 0.03 | 0.10 ± 0.03 | 0.09 ± 0.03 |
| Germ | A-1[b] | n/a[d] | 0.10 ± 0.01 | 0.10 ± 0.02 | 0.09 ± 0.02 | 0.09 ± 0.01 |
| | A-2[b] | n/a[d] | 0.12 ± 0.02 | 0.10 ± 0.01 | 0.11 ± 0.02 | 0.10 ± 0.02 |
| | B-1[b] | n/a[d] | 0.11 ± 0.02 | 0.08 ± 0.01 | 0.08 ± 0.01 | 0.08 ± 0.01 |
| | B-2[b] | n/a[d] | 0.11 ± 0.02 | 0.10 ± 0.01 | 0.10 ± 0.01 | 0.09 ± 0.01 |
| | C-1[b] | 0.11 ± 0.02 | 0.09 ± 0.02 | 0.08 ± 0.01 | 0.08 ± 0.02 | 0.08 ± 0.01 |
| | C-2[b] | n/a[d] | 0.10 ± 0.02 | 0.12 ± 0.03 | 0.10 ± 0.02 | 0.09 ± 0.02 |
| | C-3[c] | 0.12 ± 0.02 | 0.11 ± 0.02 | 0.10 ± 0.02 | 0.09 ± 0.02 | 0.09 ± 0.02 |
| | C-4[c] | 0.11 ± 0.02 | 0.11 ± 0.02 | 0.10 ± 0.01 | 0.09 ± 0.01 | 0.09 ± 0.01 |
| | D-1[c] | 0.13 ± 0.04 | 0.11 ± 0.03 | 0.09 ± 0.02 | 0.09 ± 0.02 | 0.08 ± 0.01 |

[a] Average ± one standard deviation.
[b] Samples A-1 through C-2 are coproducts from HRW wheat blends.
[c] Samples C-3, C-4, and D-1 are coproducts of HRS wheat blends.
[d] No sample remained on the U.S. sieve #8.

Particle size of ground materials is generally expressed as the geometric mean diameter, Table 5 shows the geometric mean diameter for particles retained on i[th] sieve ($\underline{d}_i$). The sieving method assumes that the $\underline{d}_i$ is equal to $(d_i \times d_{i+1})^{1/2}$ where di and $d_{i+1}$ are the nominal sieve openings of the i[th] and next larger than i[th] sieve, respectively. Therefore, if particles were retained between

U.S. Standard Sieves #6 (3.36 mm) and #8 (2.38 mm) then the $\underline{d}_i$ of the particle is assumed to be 2.828 mm, according to the ASAE (1996) method S319.2. However, the results obtained from the image analysis indicated that the equivalent projected area diameter, $d_a$, is much larger than $\underline{d}_i$. For example, the particles retained on the U.S. sieve #8 had an average of 1.7 times larger equivalent projected area diameter than $\underline{d}_i$ for bran and 1.5 times for germ samples. As sieve size decreased from U.S. sieve #8 to #30, the difference between the two diameters increased. The bran and germ particles equivalent projected area diameter was 2.2 and 2.0 times larger than the geometric mean diameter, $d_i$, respectively. Possible reasons for these sieving differences include the effect of sieve loading, duration of sieving, random orientation of particles, and sampling of material (Herdan 1960). In this particular case, the random orientation of particles to the sieve apertures could cause large differences between $d_a$ and $\underline{d}_i$. Although there would not be a difference in the case of spherical particles, with nonspherical particles not all particles can arrive at the aperture in the orientation to pass. Therefore, there is a certain probability that the particle will actually pass through the aperture. Herdan (1960) stated that particle size measured by the sieving method would not coincide with the average particle size determined by other methods, such as image analysis, because of the random orientation of particles going through the sieve aperture. Herdan (1960) also found that for moderate degrees of flakiness and elongation, the equivalent projected area diameter was 1.4 times larger than nominal sieve aperture. However, in this study it was found that the ratio between the equivalent projected area diameter and the particle thickness were within ranges of 15.7 to 37.6 for bran and 15.5 to 32.2 for germ particles. This is the result of large differences between $d_a$ and $\underline{d}_i$ because of a high degree of flakiness and elongation of bran and germ particles. The ASAE sieving method (1996) estimates the surface area and number of particles in the sample by assuming the particles having a spherical shape. Therefore, when using the results from the sieving method, surface area and number of particles cannot be accurately determined from samples with a high degree of flakiness, such as bran and germ.

## Chemical Composition

Table 6 shows analytical results for the coproducts chemical composition. All analyses are reported on a 14.0% moisture basis. Previous studies looked at the chemical composition of wheat milling coproducts like the ones evaluated in this study (Dale 1998; Hubble 1998; Farrell *et al.* 1967). Because of the changes in milling flows and wheat varieties, the results of this study were compared with the results of previous work.

TABLE 5.
EQUIVALENT PROJECTED AREA DIAMETER ($d_a$) FROM IMAGE ANALYSIS OF BRAN AND GERM FOR A GIVEN GEOMETRIC MEAN DIAMETER (mm)[a]

| Co-product | Sample | Geometric Mean Diameter ($d_i$) [b] | | | | |
|---|---|---|---|---|---|---|
| | | 2.83 | 2.00 | 1.42 | 1.00 | 0.71 |
| Bran | A-1[c] | 4.23 ± 0.36 | 3.33 ± 0.35 | 2.46 ± 0.26 | 1.83 ± 0.13 | 1.62 ± 0.16 |
| | A-2[c] | 4.05 ± 0.32 | 3.20 ± 0.35 | 2.67 ± 0.37 | 2.03 ± 0.25 | 1.71 ± 0.17 |
| | B-1[c] | 4.13 ± 0.34 | 3.33 ± 0.35 | 2.57 ± 0.34 | 1.95 ± 0.22 | 1.65 ± 0.17 |
| | B-2[c] | 4.07 ± 0.37 | 3.36 ± 0.33 | 2.64 ± 0.30 | 2.05 ± 0.23 | 1.65 ± 0.19 |
| | C-1[c] | 4.05 ± 0.33 | 3.24 ± 0.36 | 2.62 ± 0.30 | 2.00 ± 0.20 | 1.55 ± 0.16 |
| | C-2[c] | 4.09 ± 0.39 | 3.21 ± 0.31 | 2.55 ± 0.31 | 1.98 ± 0.27 | 1.77 ± 0.15 |
| | C-3[d] | 3.90 ± 0.35 | 3.10 ± 0.30 | 2.42 ± 0.28 | 1.93 ± 0.22 | 1.58 ± 0.17 |
| | C-4[d] | 4.01 ± 0.41 | 3.16 ± 0.32 | 2.47 ± 0.28 | 1.93 ± 0.23 | 1.57 ± 0.20 |
| | D-1[d] | 4.06 ± 0.44 | 3.27 ± 0.34 | 2.00 ± 0.25 | 2.00 ± 0.25 | 1.61 ± 0.19 |
| Germ | A-1[c] | n/a[e] | 2.55 ± 0.13 | 2.28 ± 0.37 | 1.73 ± 0.22 | 1.50 ± 0.18 |
| | A-2[c] | n/a[e] | 2.69 ± 0.21 | 2.34 ± 0.14 | 1.85 ± 0.11 | 1.57 ± 0.20 |
| | B-1[c] | n/a[e] | 2.60 ± 0.26 | 2.22 ± 0.20 | 1.80 ± 0.19 | 1.38 ± 0.13 |
| | B-2[c] | n/a[e] | 2.81 ± 0.21 | 2.18 ± 0.13 | 1.85 ± 0.11 | 1.53 ± 0.10 |
| | C-1[c] | 3.47 ± 0.51 | 2.78 ± 0.29 | 2.22 ± 0.21 | 1.79 ± 0.17 | 1.52 ± 0.12 |
| | C-2[c] | n/a[e] | 2.62 ± 0.30 | 2.19 ± 0.21 | 1.74 ± 0.15 | 1.55 ± 0.13 |
| | C-3[d] | 3.66 ± 0.44 | 2.92 ± 0.31 | 2.34 ± 0.23 | 1.77 ± 0.15 | 1.55 ± 0.12 |
| | C-4[d] | 3.03 ± 0.52 | 3.10 ± 0.32 | 2.45 ± 0.18 | 1.79 ± 0.12 | 1.53 ± 0.10 |
| | D-1[d] | 4.05 ± 0.44 | 3.07 ± 0.34 | 2.27 ± 0.22 | 1.83 ± 0.177 | 1.66 ± 0.16 |

[a] Average ± one standard deviation.
[b] Geometric mean diameter of particles on $i^{th}$ sieve in mm.
[c] Samples A-1 through C-2 are coproducts from HRW wheat blends.
[d] Samples C-3, C-4, and D-1 are coproducts of HRS wheat blends.
[e] No sample remained on the sieve.

Ash content of bran samples (5.57% average) were the highest among the coproducts studied, while germ and shorts had similar ash content (4.17 and 4.10% average, respectively). Red dog had the lowest ash content (3.08% average). The average ash content for bran obtained in this study was lower than those from Hubble (1998) and Dale (1998) who were found to be 6.84 and 6.18%, respectively; but it was within the range of the results from Farrell *et al.* (1967). The ash content of bran from the KSU pilot mill (samples A-1 and 2) is higher than those from the commercial flour mills. The KSU pilot mill has

TABLE 6.
PROXIMATE ANALYSIS OF COPRODUCTS (%)[a]

| Co-product | Sample | Ash | Protein | Lipid | Fiber |
|---|---|---|---|---|---|
| Bran | A-1[b] | 6.16 | 14.7 | 1.03 | 10.96 |
| | A-2[b] | 6.15 | 13.3 | 3.04 | 9.33 |
| | B-1[b] | 5.73 | 13.1 | 1.76 | 11.70 |
| | B-2[b] | 5.54 | 16.2 | 2.91 | 9.63 |
| | C-1[b] | 4.74 | 14.7 | 2.16 | 8.78 |
| | C-2[b] | 4.78 | 14.4 | 1.84 | 8.61 |
| | C-3[c] | 5.71 | 16.3 | 2.76 | 8.81 |
| | C-4[c] | 5.55 | 17.0 | 2.68 | 8.70 |
| | D-1[c] | 5.74 | 15.8 | 2.70 | 9.04 |
| Germ | A-1[b] | 4.50 | 24.6 | 8.04 | 3.69 |
| | A-2[b] | 4.03 | 24.2 | 8.83 | 3.59 |
| | B-1[b] | 4.19 | 27.8 | 10.10 | 2.65 |
| | B-2[b] | 4.11 | 28.1 | 10.34 | 2.72 |
| | C-1[b] | 3.74 | 22.4 | 5.91 | 4.08 |
| | C-2[b] | 3.75 | 21.1 | 5.60 | 4.64 |
| | C-3[c] | 4.50 | 24.6 | 6.99 | 3.56 |
| | C-4[c] | 4.71 | 25.4 | 7.38 | 4.02 |
| | D-1[c] | 3.97 | 20.4 | 4.68 | 5.41 |
| Shorts | A-1[b] | 4.14 | 15.3 | 2.80 | 7.76 |
| | A-2[b] | 3.73 | 15.3 | 3.93 | 6.32 |
| | B-1[b] | 3.58 | 14.3 | 3.39 | 6.96 |
| | B-2[b] | 4.52 | 17.0 | 2.78 | 8.12 |
| | D-1[c] | 4.56 | 17.7 | 3.06 | 7.76 |
| Red dog | A-1[b] | 3.48 | 16.0 | 4.64 | 5.14 |
| | A-2[b] | 3.16 | 14.9 | 4.78 | 3.89 |
| | B-1[b] | 1.99 | 13.4 | 2.53 | 2.82 |
| | B-2[b] | 2.45 | 13.5 | 2.97 | 3.44 |
| | C-1[b] | 3.11 | 15.0 | 2.57 | 5.84 |
| | C-2[b] | 3.27 | 14.4 | 2.79 | 6.73 |
| | C-3[c] | 3.35 | 15.4 | 2.76 | 5.44 |
| | C-4[c] | 3.72 | 16.1 | 3.23 | 6.64 |
| | D-1[c] | 3.20 | 16.1 | 3.41 | 5.52 |

[a] All results at 14.0% wet moisture basis.
[b] Samples A-1 through C-2 are coproducts from HRW wheat blends.
[c] Samples C-3, C-4, and D-1 are coproducts of HRS wheat blends.

more roll, sifter, and purifier surface per flour produced than commercial mills; thus, contributing to better separation of endosperm from bran, separation that causes the higher ash content in the bran. Average ash content of germ from this study was similar to Hubble (1998) and Farrell *et al.* (1967), but lower than Dale (1998) who determined to be 5.12%. There was a noticeable difference in ash content for shorts between this study and published data, the ash content reported by Hubble (1998) was lower (2.44%) while Dale (1998) was considerably higher (7.92%) than that of this study (4.11%). Ash content range for red dog determined in this study was between 1.99 and 3.72 higher than that reported by Farrell *et al.* (1967), 1.99 to 2.70%. The ash content of red dog was not reported by Hubble (1998) or Dale (1998).

Among coproducts, the highest protein content is generally found in germ and the next highest in shorts (Hubble 1998; Dale 1998; Farrell *et al.* 1967). These findings held for this study. Protein content of the germ (20.4 - 28.1%) was considerably higher than the rest of coproducts, while other coproducts had similar protein contents (13.1 to 17.7%). The protein content of bran was slightly higher for HRS wheat (samples C-3, C-4, and D-1) than other wheat coproducts samples (Table 6). The protein content of wheat varies with its class, HRS wheat generally shows higher protein content than HRW wheat. Protein content of dry wheat milling products have also shown a strong relationship to protein content of raw grain (Flores *et al.* 1991; Kim *et al.* 1995). For this reason, millers often select wheat blends based on protein content to obtain a particular type of flour.

Lipid content determined in this study had the greatest variation among samples for all coproducts, coefficients of variation of 29.6, 27.6, 14.3, 26.2% were found for bran, germ, shorts, and red dog, respectively. Average lipid content for bran and shorts was lower than published data while the other two coproducts had similar values. The lipid content of pure germ varies widely among different wheat classes (Shurpalekar and Rao 1977). Variation in lipid content among samples more likely happened because of differences in purity of the germ tested in this study. Fiber content of bran, germ, and shorts were very close to existing data, however, that of red dog had a higher fiber content than that reported by Farrell *et al.* (1967). A large variation of fiber was observed for germ and red dog samples (21.9 and 27.4%, respectively). The germ from the commercial milling processes might contain a large bran amount, which is high in fiber depending on the milling flow. A linear regression showed a significant ($P < 0.01$) negative relationship between lipid and fiber content. This could indicate that the samples with low lipid content were contaminated with a larger amount of bran.

**Thermal Properties**

The thermal conductivity results for the coproducts are shown in Table 7. Ranges of thermal conductivity for bran, germ, shorts, and red dog were 0.049 to 0.074, 0.054 to 0.0907, 0.057 to 0.076, and 0.063 to 0.080 $W(mK)^{-1}$, respectively. Thermal conductivity of coproducts was lower than that of whole wheat thermal conductivity at similar moisture contents [0.128 to 0.142 $W(mK)^{-1}$, ASAE 1998] and that of wheat flour [0.117 $W(mK)^{-1}$] reported by Buhri and Singh (1993).

Moisture content has a significant effect on thermal conductivity of grain, grain products, and food (Baghr-Khandan *et al.* 1981; Rahman 1995). The coefficient of determination ($R^2$) in this study indicated that the moisture content was a strong predictor of thermal conductivity of coproducts. The lowest $R^2$ found was 0.753 from germ while the highest $R^2$ (0.999) was observed in bran and shorts. Ranges of $R^2$ were 0.791 to 0.999, 0.770 to 0.980, 0.780 to 0.999, and 0.772 to 0.970 for bran, germ, shorts, and red dog, respectively.

The specific heat, defined as the amount of heat necessary to raise the temperature of one unit mass of coproducts, was: 1.29, 1.56 and 1.60 $kJ(kgK)^{-1}$ for bran; 1.08, 1.51 and 1.94 kJ/kgK for germ; and 1.51, 1.61 and 1.78 $kJ(kgK)^{-1}$ for red dog; all results at 8, 12 and 16% moisture content, respectively. For shorts the specific heat was 1.57 $kJ(kgK)^{-1}$ at 8% moisture content. The highest specific heat was obtained from a germ sample at 16% moisture content, and the lowest from germ at 8% moisture content. In terms of the wheat class and for the moisture range studied (8 to 16%), the specific heat determined for HRW coproducts were: 1.29, 1.51, 1.57, and 1.54 $kJ(kgK)^{-1}$ for bran, germ, shorts and red dog, respectively; and for HRS coproducts were: 1.58, 1.51, 1.49, and 1.78 $kJ(kgK)^{-1}$ for bran, germ, shorts and red dog, respectively. The specific heat ranges for coproducts were wider than specific heats reported for whole wheat kernel [1.55 to 1.63 $kJ(kgK)^{-1}$] and wheat flour [1.66 $kJ(kgK)^{-1}$] in ASAE (1998), and whole wheat flour [1.805 to 1.846 $kJ(kgK)^{-1}$] in Gupta (1990). No data for the thermal conductivities and specific heat for wheat coproducts were found in the literature.

## CONCLUSIONS

Product characterization is the first step in adding value to a raw material. Physical, chemical, and thermal properties of wheat milling coproducts from three commercial flour mills and one pilot wheat flour mill were determined. True and bulk densities and thermal conductivity of coproducts were highly predictable from moisture changes. The thickness of bran determined in this study was larger than that of microscopy studies, as a result of different methods

TABLE 7.
THERMAL CONDUCTIVITY OF COPRODUCTS AT DIFFERENT MOISTURE CONTENT [W(mK)$^{-1}$]

| Sample | Moisture (%)[a] | Bran | Germ | Shorts | Red dog |
|---|---|---|---|---|---|
| A-1[b] | 8 | 0.051 | 0.060 | 0.062 | 0.067 |
| | 12 | 0.061 | 0.067 | 0.053 | 0.070 |
| | 16 | 0.062 | 0.080 | 0.072 | 0.079 |
| A-2[b] | 8 | 0.053 | 0.056 | 0.063 | 0.066 |
| | 12 | 0.059 | 0.068 | 0.065 | 0.076 |
| | 16 | 0.065 | 0.090 | 0.073 | 0.078 |
| B-1[b] | 8 | 0.052 | 0.064 | 0.058 | 0.069 |
| | 12 | 0.055 | 0.074 | 0.062 | 0.077 |
| | 16 | 0.056 | 0.080 | 0.070 | 0.081 |
| B-2[b] | 8 | 0.050 | 0.065 | 0.059 | 0.071 |
| | 12 | 0.054 | 0.088 | 0.067 | 0.079 |
| | 16 | 0.070 | 0.089 | 0.076 | 0.080 |
| C-1[b] | 8 | 0.051 | 0.061 | n/p[d] | 0.064 |
| | 12 | 0.061 | 0.078 | n/p[d] | 0.073 |
| | 16 | 0.070 | 0.079 | n/p[d] | 0.078 |
| C-2[b] | 8 | 0.050 | 0.065 | n/p[d] | 0.063 |
| | 12 | 0.065 | 0.070 | n/p[d] | 0.065 |
| | 16 | 0.066 | 0.070 | n/p[d] | 0.074 |
| C-3[c] | 8 | 0.050 | 0.055 | n/p[d] | 0.067 |
| | 12 | 0.059 | 0.073 | n/p[d] | 0.077 |
| | 16 | 0.074 | 0.076 | n/p[d] | 0.077 |
| C-4[c] | 8 | 0.046 | 0.059 | n/p[d] | 0.066 |
| | 12 | 0.058 | 0.071 | n/p[d] | 0.076 |
| | 16 | 0.067 | 0.074 | n/p[d] | 0.077 |
| D-1[c] | 8 | 0.055 | 0.060 | 0.060 | 0.062 |
| | 12 | 0.057 | 0.066 | 0.066 | 0.069 |
| | 16 | 0.061 | 0.069 | 0.071 | 0.072 |

[a] Moisture content in wet basis.
[b] Samples A-1 through C-2 are coproducts from HRW wheat blends.
[c] Samples C-3, C-4, and D-1 are coproducts of HRS wheat blends.
[d] Shorts were not produced in commercial mill 2.

of sample preparation. The average thickness and equivalent projected area diameter of individual particles of bran and germ samples were significantly affected ($P < 0.05$) by different wheat classes and milling flows. Separation by the sieving method significantly affected thickness of bran and germ samples. Geometrical mean diameter ($d_i$) of particles was much smaller than equivalent projected area diameter ($d_a$), because of the random orientation of a particle when it passes through an aperture in a sieve. Wheat flour milling flows and variability in the composition of the wheat blend processed by the flour mill will determine the composition and characteristics of the coproducts manufactured. Nonetheless, the results of this study showed the characterization ranges for the major physical and thermal properties, filled the information gaps and updated previous chemical composition studies for wheat milling coproducts of limited scope or not previously available.

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